Overview of the Development of the Solar Electric Propulsion Technology Demonstration Mission 12.5-kW Hall Thruster

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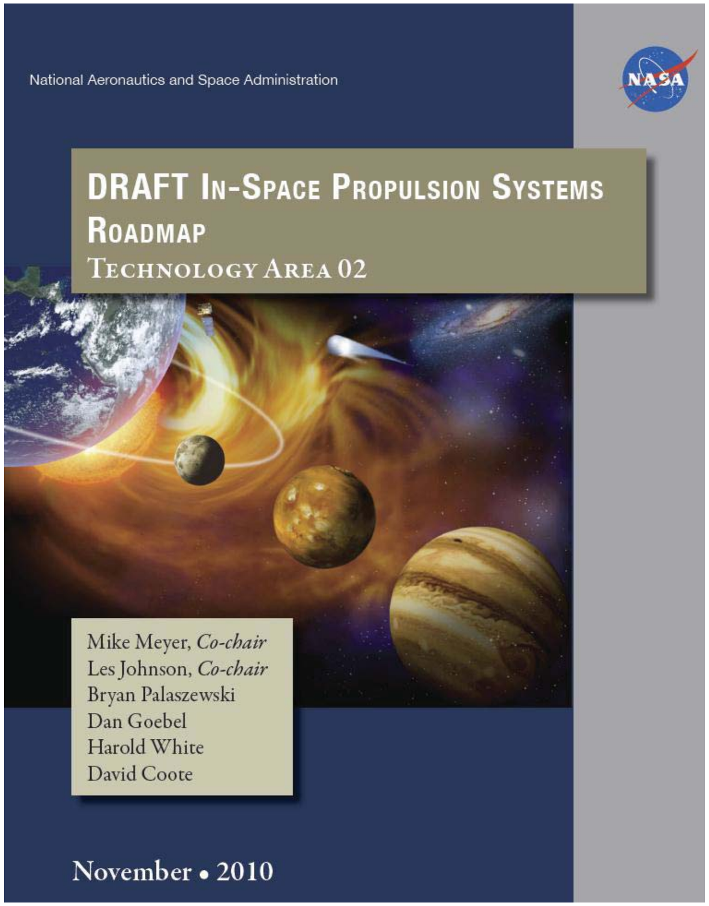
Outline

- NASA's In Space Propulsion Roadmap
- NASA's Solar Electric Propulsion Technology Demonstration Mission (SEP TDM)
- NASA GRC & JPL High Power Hall Thruster Technology Development
    - Overview of the NASA-300MS design and testing
    - 12.5 kW Hall thruster design and modeling
    - 12.5 kW Hall thruster functional tests
    - 12.5 kW thruster planned tests
- Summary

NASA's In-Space Propulsion Systems Roadmap Identified High Power EP Development as a Top Priority

- NASA's In-Space Propulsion Systems Roadmap ranked the major technical challenges for In-Space Propulsion Systems.
  - The challenges were ranked and prioritized based on mission need and perceived impact on future in-space transportation.
- The development of high power PPUs ranked #1.
- The development of high power SEP propulsion system was ranked #3.
- NASA exploration architectures beyond Low Earth Orbit (LEO) enhanced by high power SEP.



Rank	Description
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems
2	Long-term in-space cryogenic propellant storage and transfer
3	High power (e.g. 50–300 kW) class Solar Electric Propulsion scalable to MW class I
4	Advanced in-space cryogenic engines and supporting components
5	Developing and demonstrating MEMS-fabricated electrospray thrusters

Solar Electric Propulsion Technology Demonstration Mission

- NASA identified the critical technologies needed for future human exploration architectures beyond LEO and a plan for an SEP Technology Demonstration Mission (TDM) to demonstrate those technologies in an integrated vehicle

- A 30 kW-class SEP TDM is currently in pre-Phase A formulation
  - Developed and evaluated a total of 17 mission concepts to date
  - Technologies directly applicable or extensible toward higher power capability for human exploration

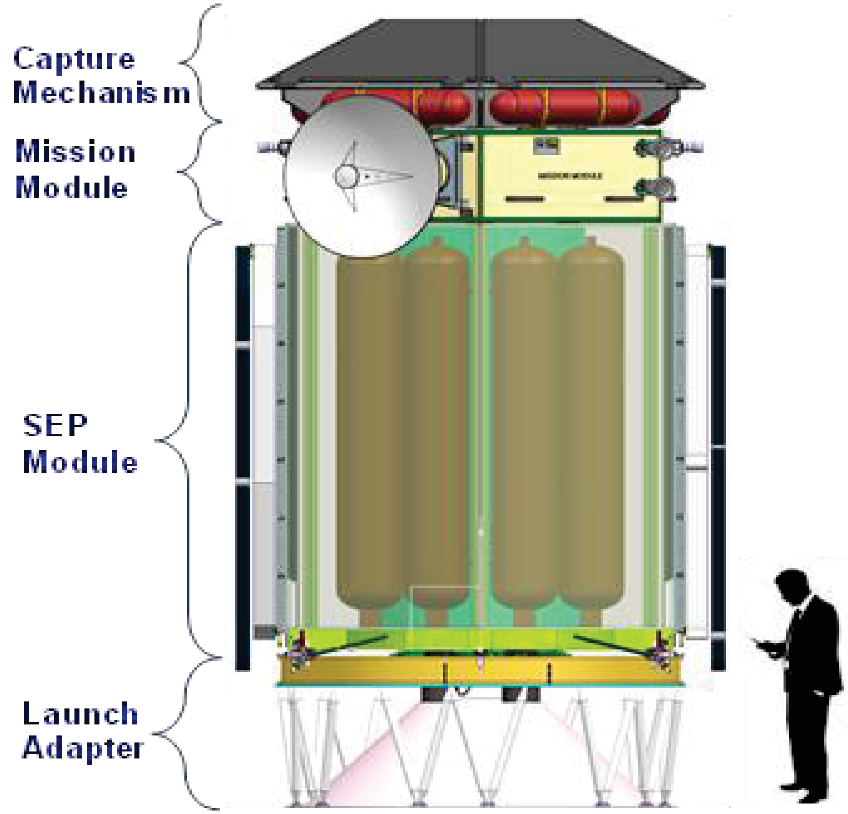
- The four top-level objectives of the SEP TDM Project are:
  - **Technology**: Demonstrate enabling SEP technologies in all relevant space environments (from LEO to beyond GEO);
  - **Extensibility:** Provide an evolutionary step to the high power SEP systems needed for future human exploration;
  - **Integrated System:** Solve the system technology and operational issues related to implementation of a high performance SEP vehicle; and
  - **Capability:** Provide a valuable new beyond-LEO payload delivery capability

Solar Electric Propulsion Technology Demonstration Mission

- The Asteroid Redirect Robotic Mission (ARRM) involving a partnership with the STMD and Human Exploration and Operations Mission Directorate (HEOMD) is one of the candidate SEP TDMs

- ARRM is enabled by high power *SEP*, using a robotic spacecraft equipped with a high-power SEP system to rendezvous with, capture, and redirect a small asteroid with a mass of up to 1000 tons to a long-term stable lunar

- ARRM is an ideal platform that meets all of the SEP TDM objectives and could serve as direct infusion of the Asteroid Robotic Vehicle (potentially with block upgrade) into human exploration architectures beyond LEO



Asteroid Retrieval Vehicle

(Ref. Brophy IEPC 2013-082)

High Power Electric Propulsion Technology Project

Developing and demonstrating Hall thruster power electronics at high-power level

15 kW PPU with input voltage of 300 Vdc & output voltage of 400 Vdc (SiC Mosfets)

14 kW PPU with input voltage of 120 Vdc & output voltage of 800 Vdc

Direct Drive Unit (DDU)

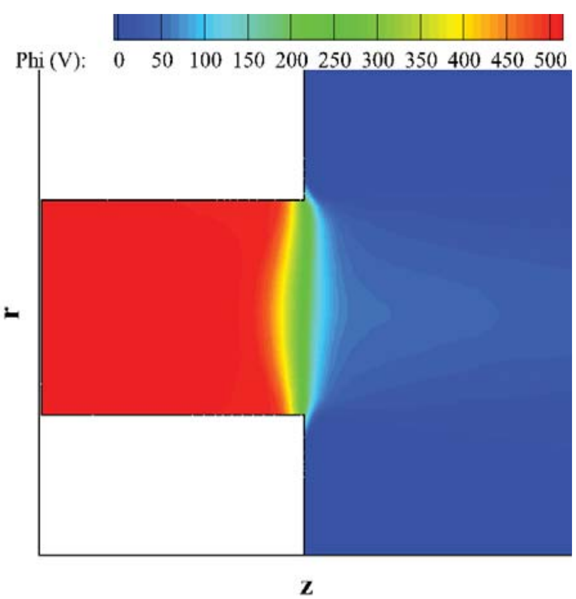
Designing, fabricating, and testing of long-life Hall technology demonstration thrusters for demonstration on SEP TDM

Retrofit existing 6 kW (H6) & 20 kW-class (NASA 300-M) Hall thruster to demonstrate magnetic shielding (MS)
- Provided risk reduction to implementation of magnetic shielding on high power class Hall thrusters

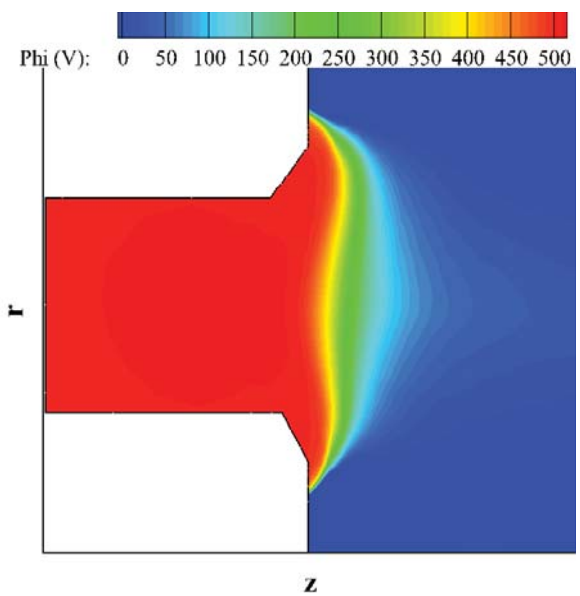
12.5 kW long-life 3,000 sec high-fidelity TDU Hall thruster
- Design & fabrication complete
- Candidate for a number of SEP TDMs including ARRM

NASA-300 Magnetically Shielded Thruster Development
Plasma and Magnetic Modeling

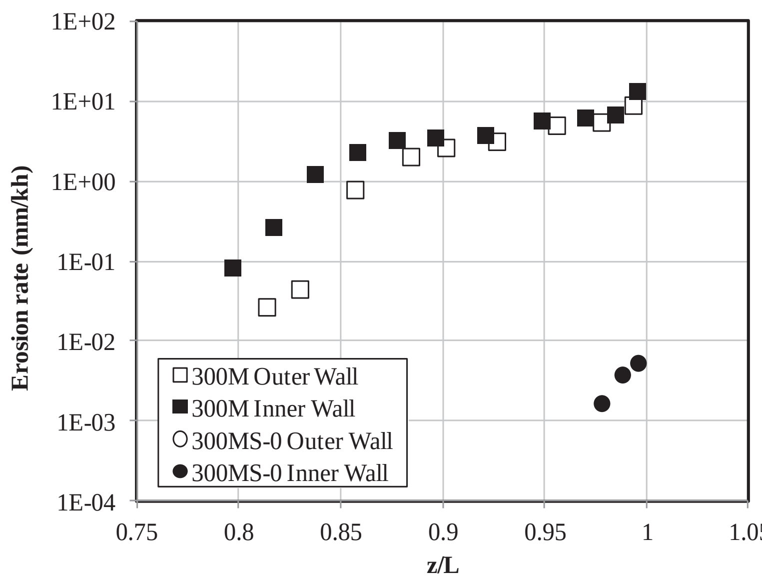
- NASA GRC and JPL Collaborated to modify the NASA-300M to attain a magnetically shielded configuration
- Extensive magnetic modeling and plasma modeling was performed to finalize the NASA-300MS magnetic field topology
- Modified the NASA-300M magnetic circuit and confirmed that the modifications resulted in a magnetic-shielded configuration by mapping the *300MS* magnetic field



300M

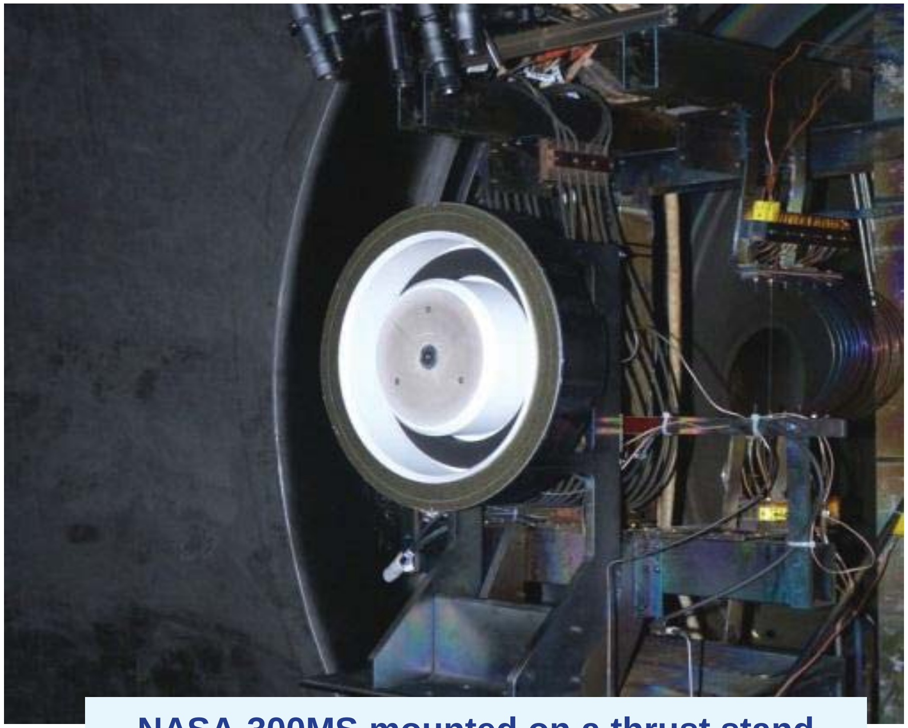


300MS



NASA-300 MS Thruster Testing At NASA GRC

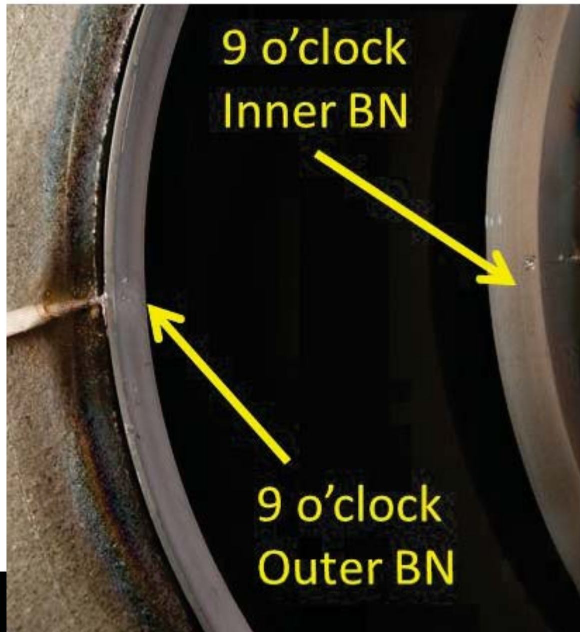
NASA GRC's VF5 vacuum chamber

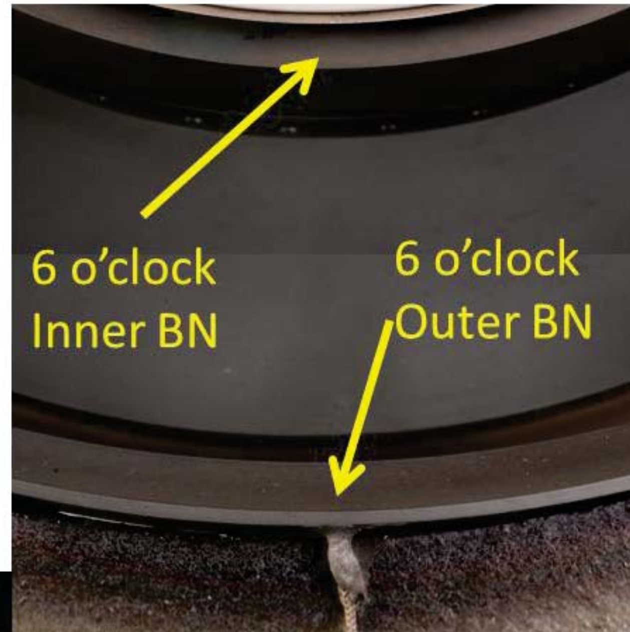

NASA-300MS mounted on a thrust stand inside NASA GRC's VF5

- Testing performed at NASA GRC VF5 vacuum chamber

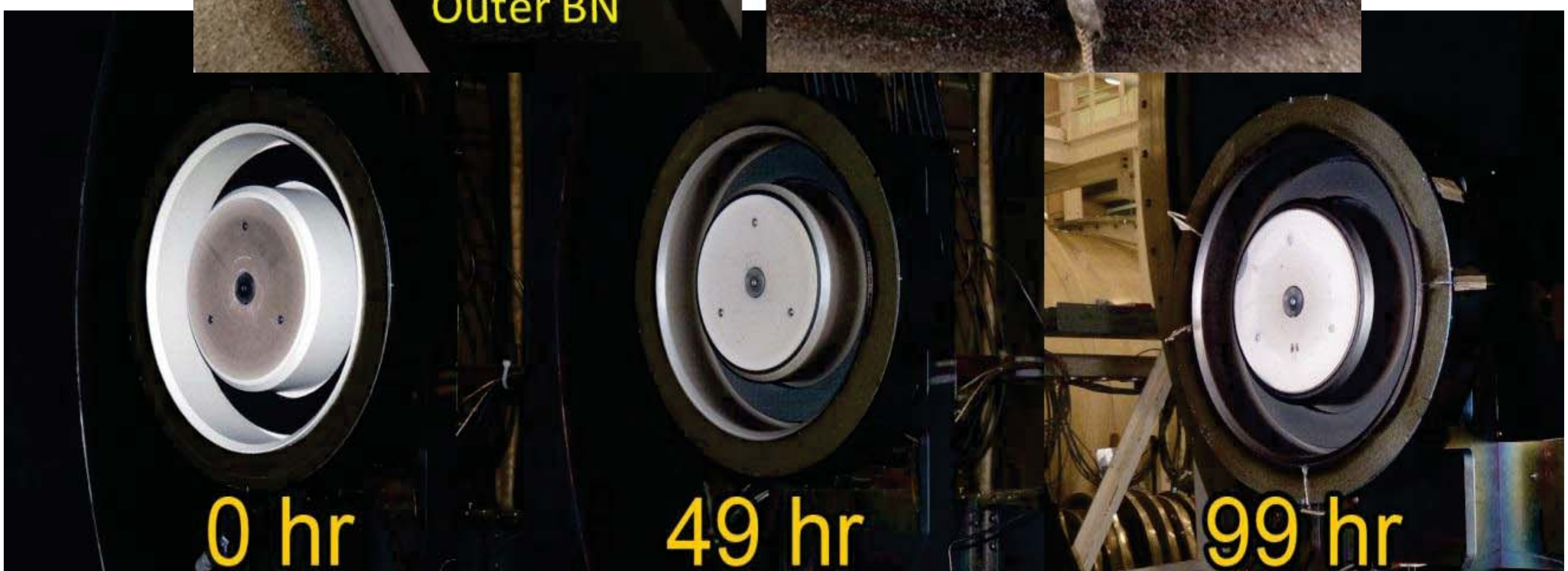
NASA GRC's VF5 is the highest pumping speed vacuum facility for electric propulsion testing in US

NASA-300MS Visual Inspection Provided Preliminary Confirmation of Magnetic Shielding



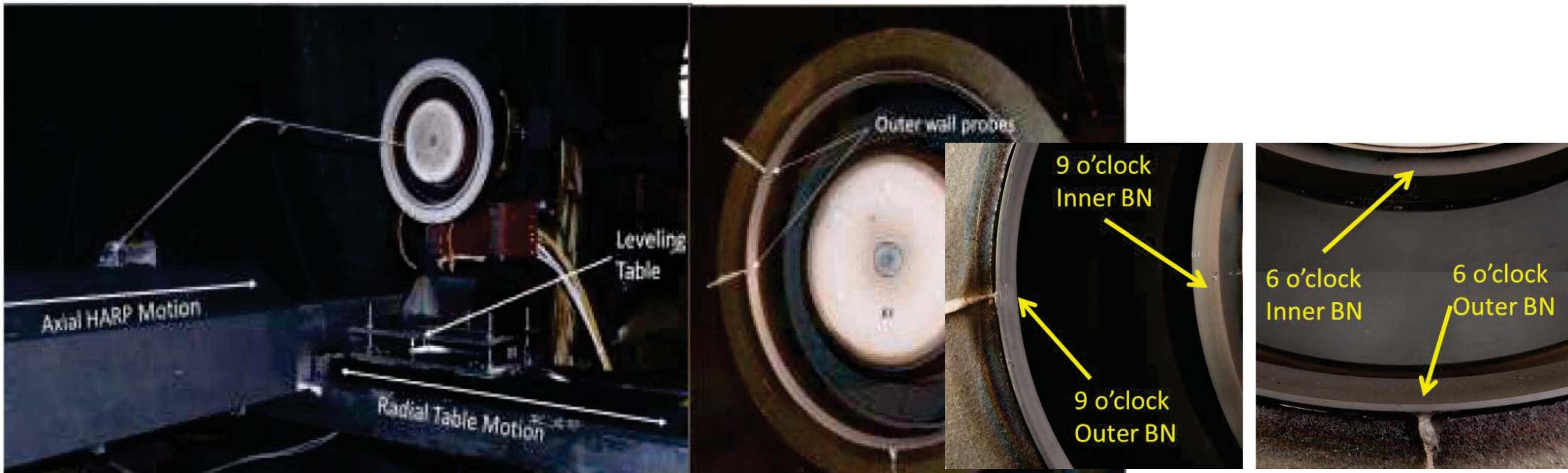


NASA-300M discharge channels



Darkening of discharge channel ceramic indicates back-sputtered efflux from facility exceeds channel erosion rate

Plasma Measurements on the Discharge Channel Walls Confirmed the Attainment of Magnetic Shielding



	Plasma Potential, V	
Operating Condition	Inner Wall	Outer Wall
300 V, 10 kW	310	305
300 V, 15 kW	311	304
400 V, 15 kW	410*	402
400 V, 20 kW	413*	408
500 V, 20 kW	508*	501
600 V, 20 kW	600*	603

Anode potentials were measured on the discharge chamber inner and outer walls for all test conditions

The NASA-300MS Performance is Comparable to the NASA-300M

Discharge Voltage, V	Discharge Power, kW	300M		300MS		300MS-2	
		η_{T}, %	$I_{sp, T}$, sec	η_{T}, %	$I_{sp, T}$, sec	η_{T}, %	$I_{sp, T}$, sec
300	15	62	2,010	60	2,090	60	2,120
400	20	66	2,440	64	2,420	63	2,440
500	20	66	2,700	64	2,700	64	2,700
600	20	65	2,910	63	2,880	64	2,880
700	20					63	3,050

- Efficiency differences within measurement uncertainty
- NASA 300MS configurations 1 & 2 were tested (different length discharge chamber)
  - 300MS-1 discharge channel length 100% of 300-M
  - 300MS-2 discharge channel length 80% of 300-M

Long Life High Power Hall Thruster Development

Thruster Attribute	12.5 kW
Nominal Power, kW	12.5 kW
Discharge Voltage, V	200-800 V
Discharge Current, A	≤31 A
Performance: Total Thrust Efficiency & Specific Impulse	≥ 60% @ BOL ≥ 3,000 sec @ BOL
Xenon Throughput, Kg	≥ 3,300
Specific Mass, kg/kW	≤ 3 kg/kW
Environmental- Thermal	• Inner solar system operations with any sun angle/distance relationship at 0.7 AU • Deep space facing at up to 3.0 AU
Environmental- Vibration	Delta IV Launch Load Levels

12.5 kW Hall Thruster Modeling and Design

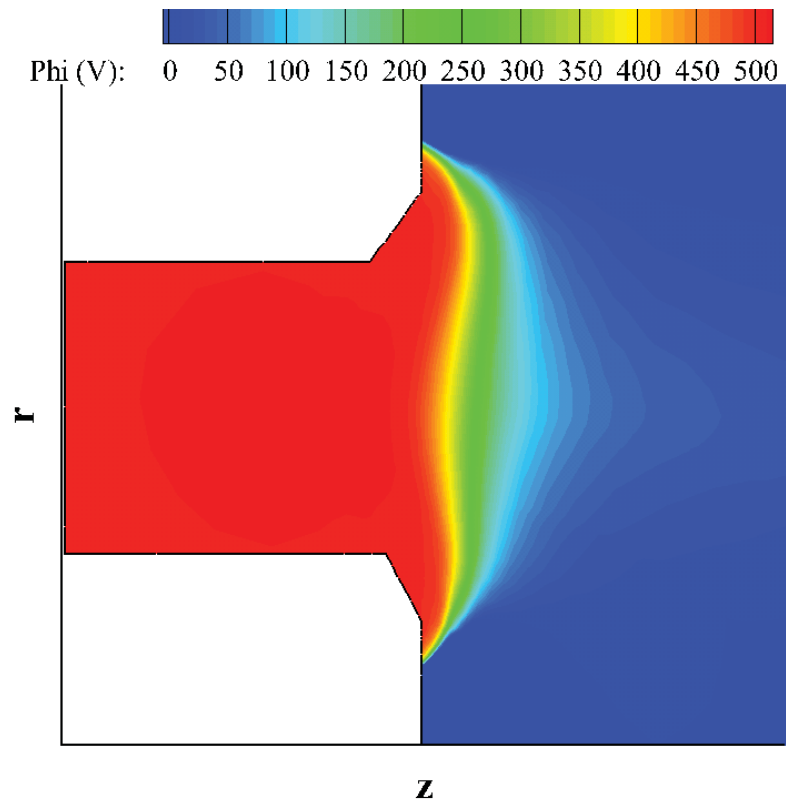
- In August of 2013, the NASA GRC and the JPL Hall thruster design team initiated tasks to design, model, fabricate, and test a 12.5 kW class long-life, high performance, 3,000 s capable Hall thruster

- The thruster design activity leveraged the extensive NASA H6MS and NASA-300MS thruster designs and test experiences

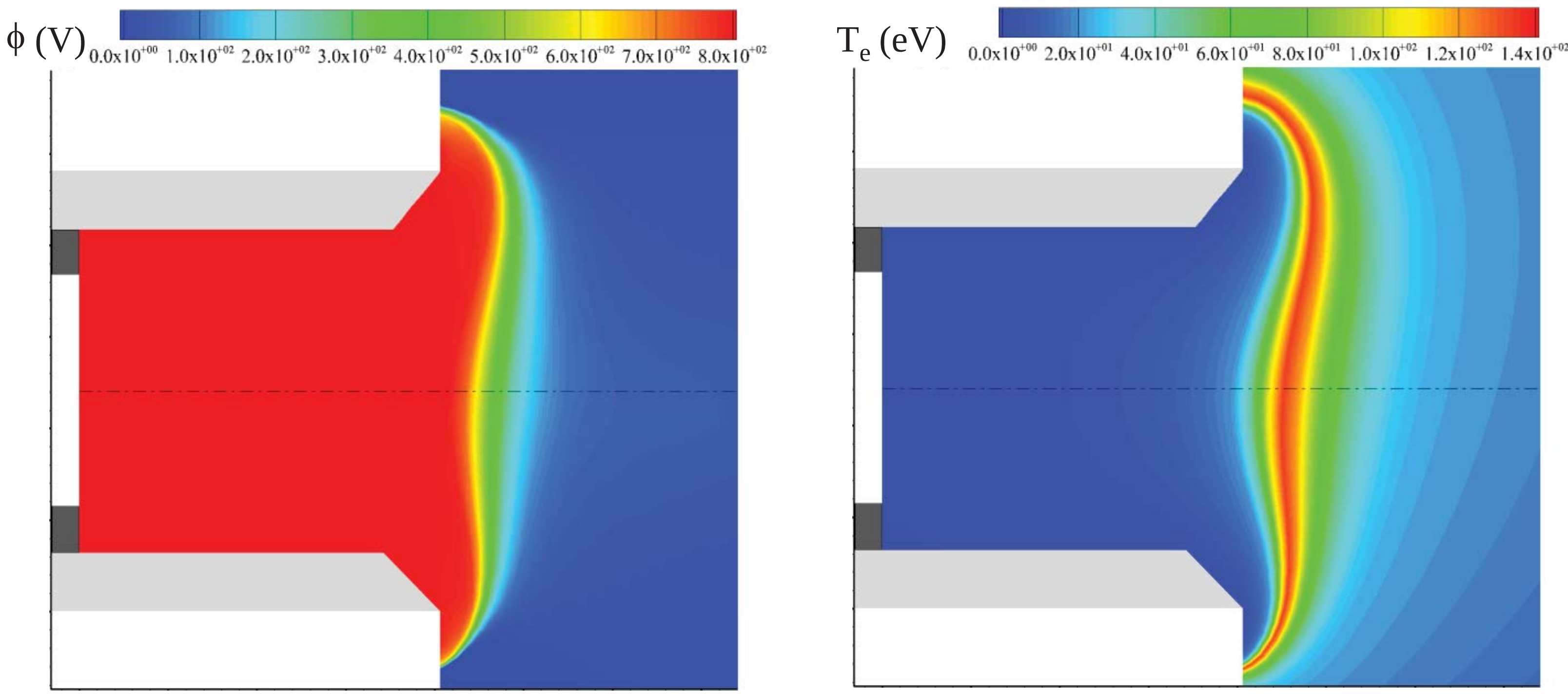
- Extensive magnetic circuit modeling and plasma modeling (Hall2De) were performed to select the final 12.5 kW thruster configuration

  - ➢ Three thruster configurations were modeled (magnetic and plasma modeling)

  - ➢ A down select was made based on the plasma modeling results and heritage thruster designs



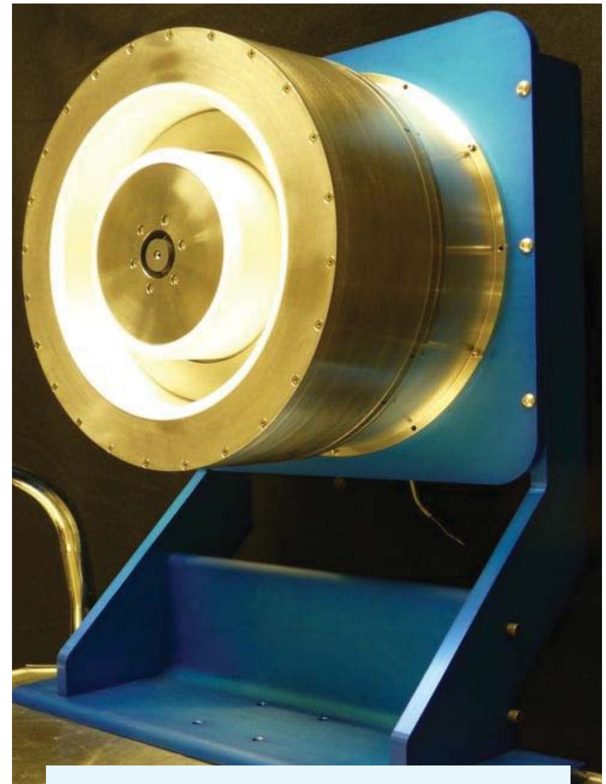
12.5 kW Hall Thruster Magnetic and Plasma Modeling



- Anode potential and low electron temperature are present along the discharge chamber inner and outer boron nitride walls, which results in reduced ion kinetic energy, reduced ion sheath energy, and reduced ion flux to these surfaces.
- The projected erosion rates were 100 to 1000 times lower than SOA.
- The magnetic and plasma modeling of the baseline configuration indicated the TDU thruster would be capable of processing greater than 3,300 kg of xenon and will achieve total thruster efficiency and specific impulse above 60% and 3,000 s, respectively

12.5 kW Hall Thruster Design

- The TDU thruster baseline configuration, as outlined by the plasma and magnetic simulations, guided the TDU thruster mechanical design.
    - **The TDU thruster magnetic circuit model provided the dimensions of the various thruster magnetic circuit components and the discharge chamber.**
- The thruster design leveraged NASA GRC's experience and lessons learned with the design of the NASA-457Mv1&v2, NASA-300M, NASA-120, NASA-173, and HiVHAc.
- TDU thruster design features include :
    - A monolithic boron nitride (BN) discharge chamber;
    - A magnetically shielded magnetic field topology;
    - A reverse flow propellant manifold with enhanced flow uniformity and protection from backsputtered materials deposition;
    - A design capable of withstanding the projected structural and thermal loads for a range of NASA TDMs; and
    - A centrally mounted cathode.



12.5 kW TDU Thruster

12.5 kW Hall Thruster Hollow Cathode

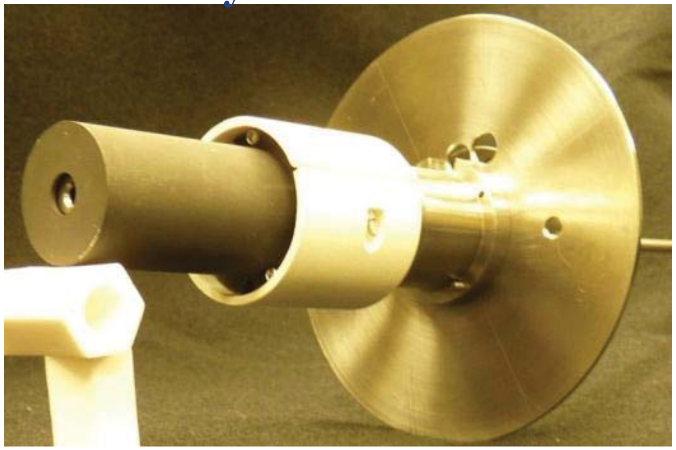
- For the 12.5 kW Hall thruster the hollow cathode assembly
  - Provide electron emission currents between 2-31 A
  - Have a service life capability > 50,000 hrs (includes emitter and other cathode components)

- The NASA Glenn and JPL team is pursuing the design of two hollow cathode assemblies

  - **<u>Assembly 1:</u>** Uses a ***barium oxide impregnated porous tungsten*** thermionic emitter
    - Used on ISS plasma contactor, NSTAR, & NEXT
    - Operates at peak temperatures of 1100-1200 ºC
    - Proposed unit is almost identical to NEXT DCA (unit tested for over 50 khrs)

  - **<u>Assembly 2:</u>** Uses a ***lanthanum hexboride (LaB_6)*** emitter
    - Used on SPT-100, and PPS-1350 Hall thrusters
    - Operates at peak temperatures of ~ 1300-1600 ºC (higher work function than BaO)
    - Requires qualification of new US heaters
    - Does not require special handling and conditioning
    - Propellant purity requirements for LaB6 cathodes are 10 to 50 times less than Ba-O cathodes
    - Large propellant tanks and loads will cause difficulty in providing high purity Xe to the cathodes

Assembly 1: BaO Cathode



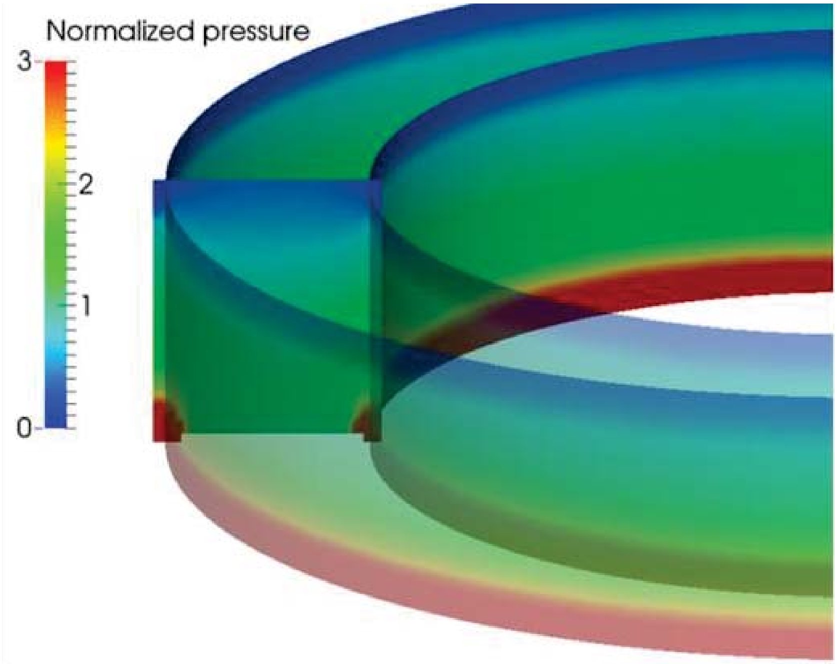
Assembly 2: LaB_6 Cathode

12.5 kW Hall Thruster Propellant Manifold Design and Modeling

- **The TDU thruster propellant manifold design is intended to provide sufficient azimuthal flow uniformity, attain improved protection against contamination from back-sputtered materials, and optimize manufacturability.**

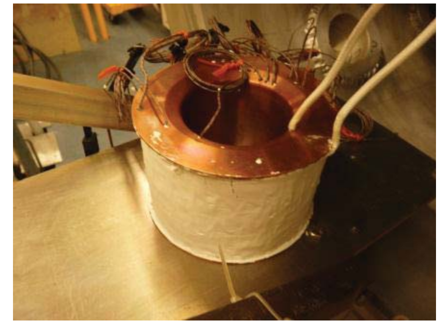
- **A quasi-1D continuum flow analysis was used to size the plenum flow to reduce azimuthal flow non-uniformity. The plenum cross section profile was optimized to reduce the azimuthal pressure delta and to minimize the number of baffle orifices.**

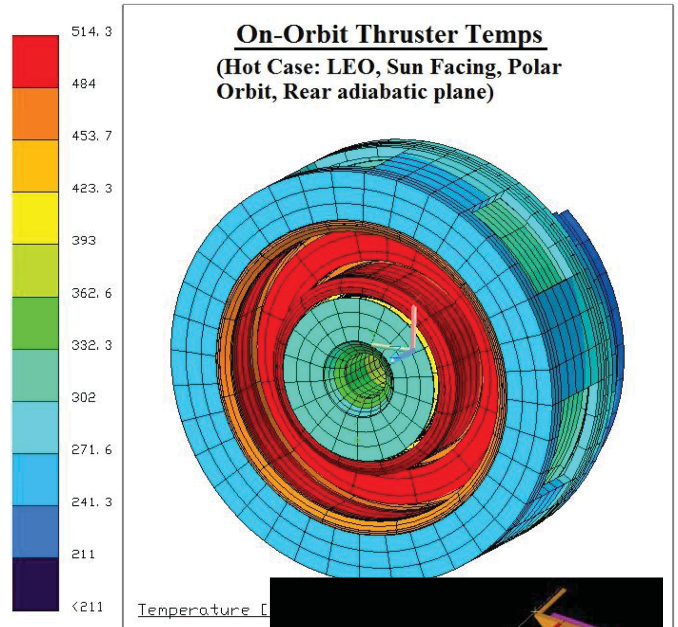
- **Direct Simulation Monte Carlo (DSMC) analysis was used to optimize the downstream flow uniformity and to balance the inner and outer flow..**

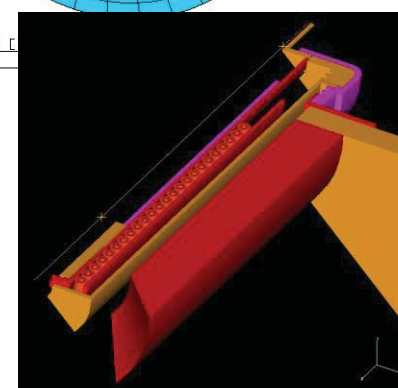


12.5 kW Hall Thruster Thermal Modeling

- **Extensive thermal modeling was performed including:**
  - **Detailed modeling of the thruster's electromagnets**
    - **An inner electromagnet test coil was fabricated and extensively instrumented to provide critical data to guide the refinement of the thermal model**
  - **Discharge chamber heat load inputs from the Hall2De model were used in the thermal model**
  - **Differential thermal growth analysis of thruster components has been performed and results used to define interface tolerances throughout the thruster assembly**
  - **Thermal modeling is being performed on worst-case project hot-thermal environment in space to confirm that thruster components temperatures will not exceed applied material limits**
  - **Cathode modeling results were provided as input to the thruster thermal model**



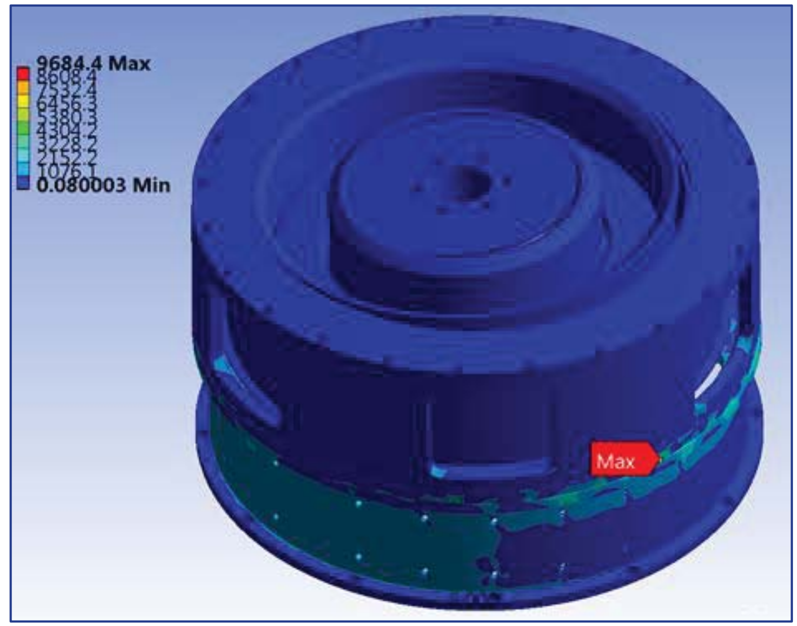




12.5 kW Hall Thruster Structural Modeling

- Extensive Structural analysis was performed including:
  - Modal analysis
  - Applied load static stress analysis
    - Positive stress margins with respect to yield strength found for all sub-components
    - Displacements remain within clearance gaps
  - Thermally-induced stress analysis
    - Thermal stress found to be an issue, design enhancements were incorporated
  - Fastener analysis
    - Fasteners found to have positive margins
  - Shock analysis
    - Shock levels at thruster are not a concern

Mode	Frequency [Hz]	Shape
1	610	Lateral bending (rocking) mode
2	630	Axial translational (bounce) mode
3	1080	Secondary lateral bending (rocking) mode

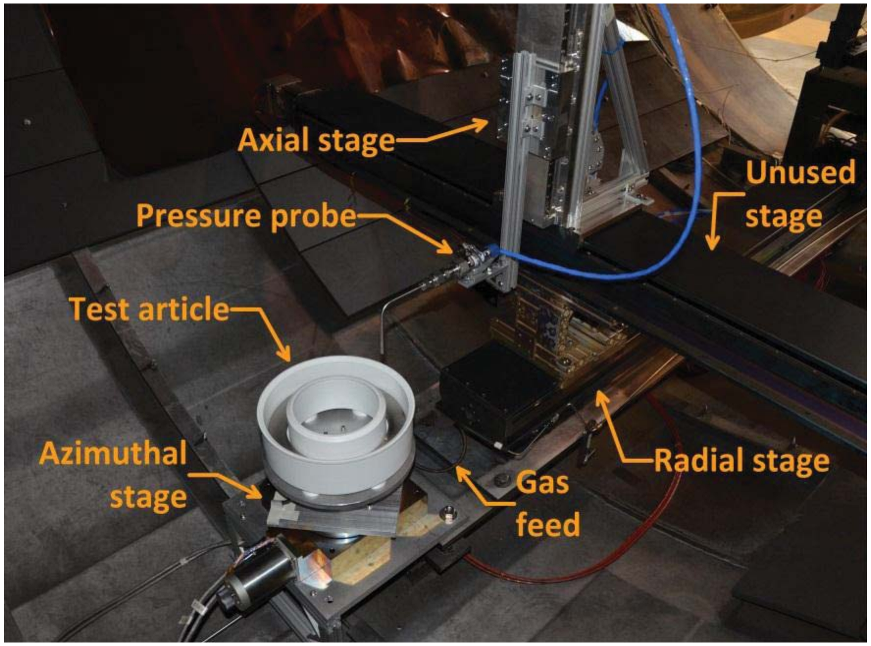


All modeling activities confirmed that the thruster design will be able to meet its design attributes

12.5 kW Technology Development Unit 1 Functional Tests

- The fabrication of TDU1 was completed in June of 2014
  - TDU2 fabrication will be completed in August of 2014

- Functional test of TDU1 were performed at NASA GRC and they included
  - ***Magnetic Testing:*** TDU1 circuit was mapped at different electromagnet settings, mapping results confirmed that a magnetically shielded configuration was attained;
  - ***Propellant Manifold Flow Measurements:*** Radial and azimuthal flow uniformity in the TDU1 thruster was quantified at different flow rates. Once performance tests are completed the thruster design team will determine acceptable flow criteria;
  - ***Voltage Isolation Tests:*** Confirmed voltage isolation capability;
  - ***Hot Fire Functional Tests:*** Hot functional test will be performed in NASA GRC's VF12 to confirm the thruster operate to operate in vacuum at 800 V, the test will also provide an initial assessment of the thruster performance.



12.5 kW Technology Development Unit 1 Functional Tests

- Extensive testing of TDU 1 will be performed at NASA GRC in the reconfigured VF5 and will include:
  - Performance acceptance and thermal characterization tests;
  - Plasma characterization tests; and
  - A short-duration wear test

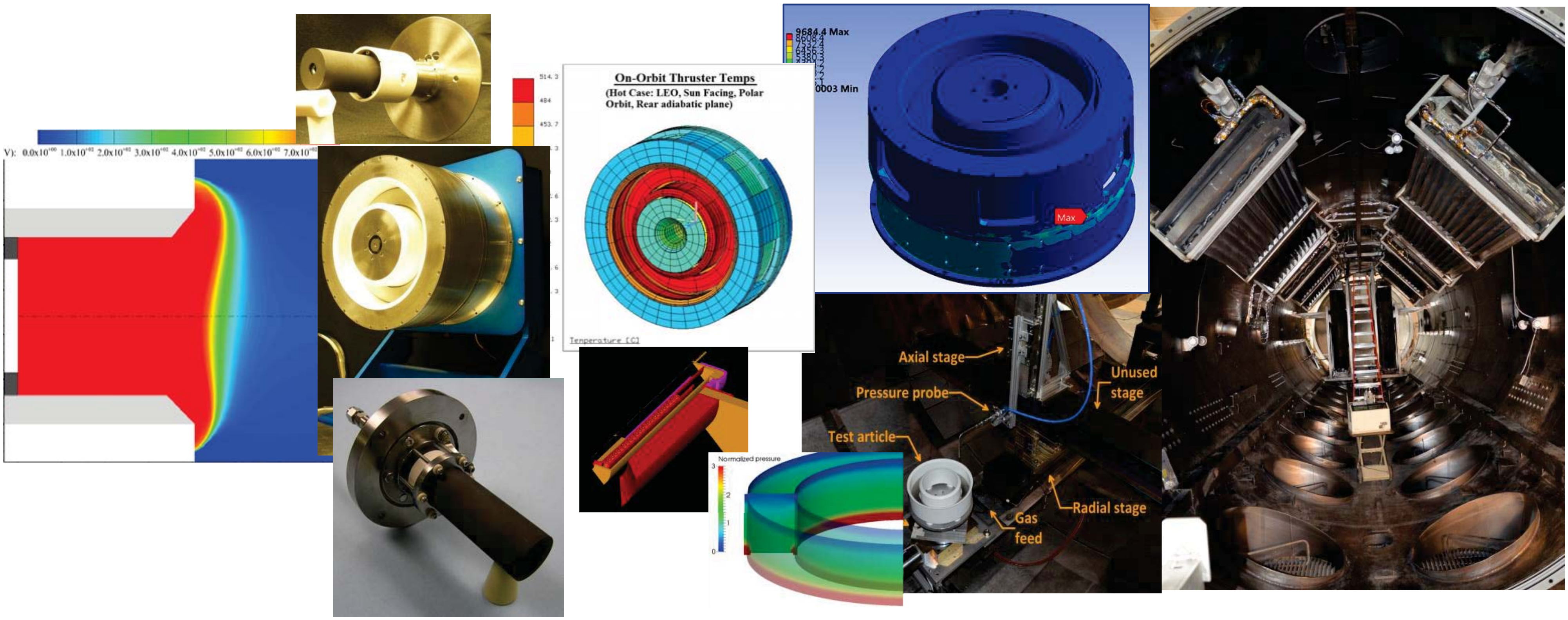
- TDU 2 will undergo performance acceptance tests at NASA GRC and will then be shipped to JPL for environmental tests that include:
  - Random vibration; and
  - Thermal vacuum

- Component Testing:
  - Hollow Cathode:
    - Wear tests will be performed at GRC and JPL; and
    - Cathode (1&2) emitter temperature and internal plasma measurements will be performed at JPL and results will be compared to OrCa2D
  - Inner electromagnet standalone tests

Photograph of VF5 after cryopanel reconfiguration

Summary

NASA GRC and JPL have designed and modeled the operation of a 12.5 kW Technology Development Unit Magnetically Shielded Hall Thruster



- NASA GRC has completed the fabrication of TDU and has completed a series of functional tests
- Starting in August, the SEP TDM TDU thruster will undergo a series of tests at NASA GRC and JPL to assess the TDU thruster performance, thermal operation, plasma properties (internal, near, and far-field), wear, and environmental response

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  - Mike Pastel, Richard Polak, Kevin McCormick, Kevin L. Blake and NASA GRC's manufacturing branch for supporting the fabrication of the 12.5 kW TDU thruster
  - George W. Readus, George P. Jacynycz, Thomas Ralys, for thruster fabrication, aid with test setup, and operation of vacuum facility 5 during the 300MS test campaign